Water Vapor Radiometers

for Site Characterization at CMB Observatories

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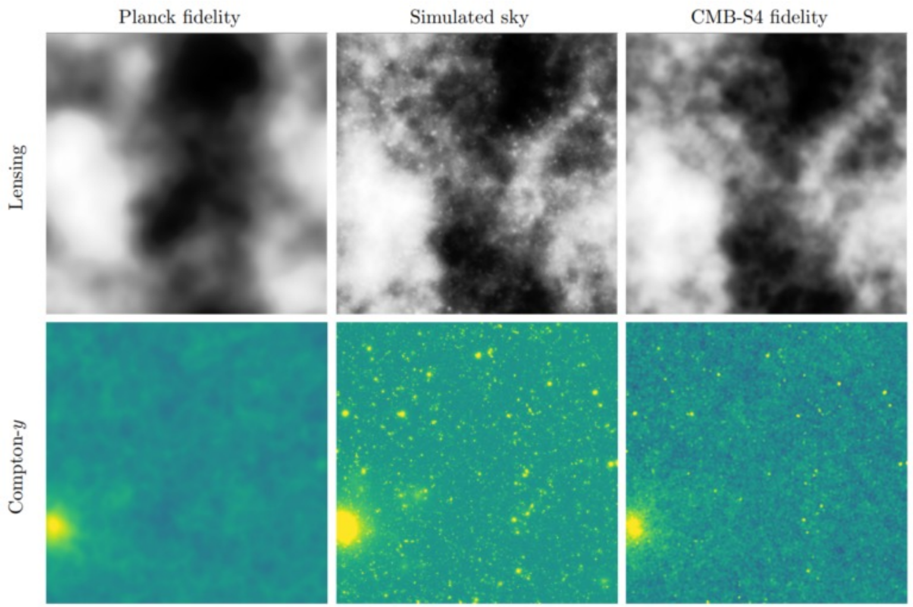
mm Universe – June 2025

Making advances in CMB Cosmology requires maximizing the sensitivity of our instruments.

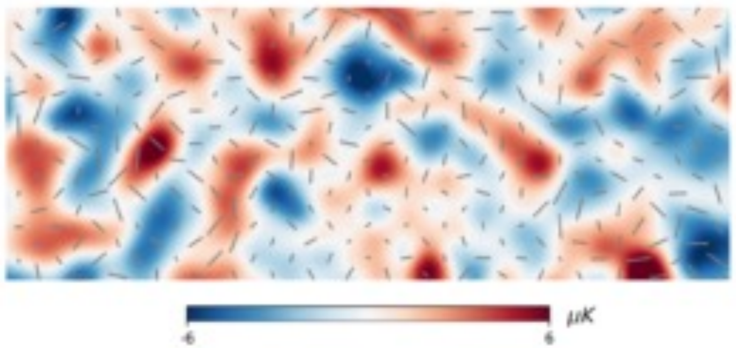
To get there, we have to mitigate noise sources like

- Detector noise
- Ground pick-up
- Thermal loading
- Radio-frequency interference
- Atmospheric Effects



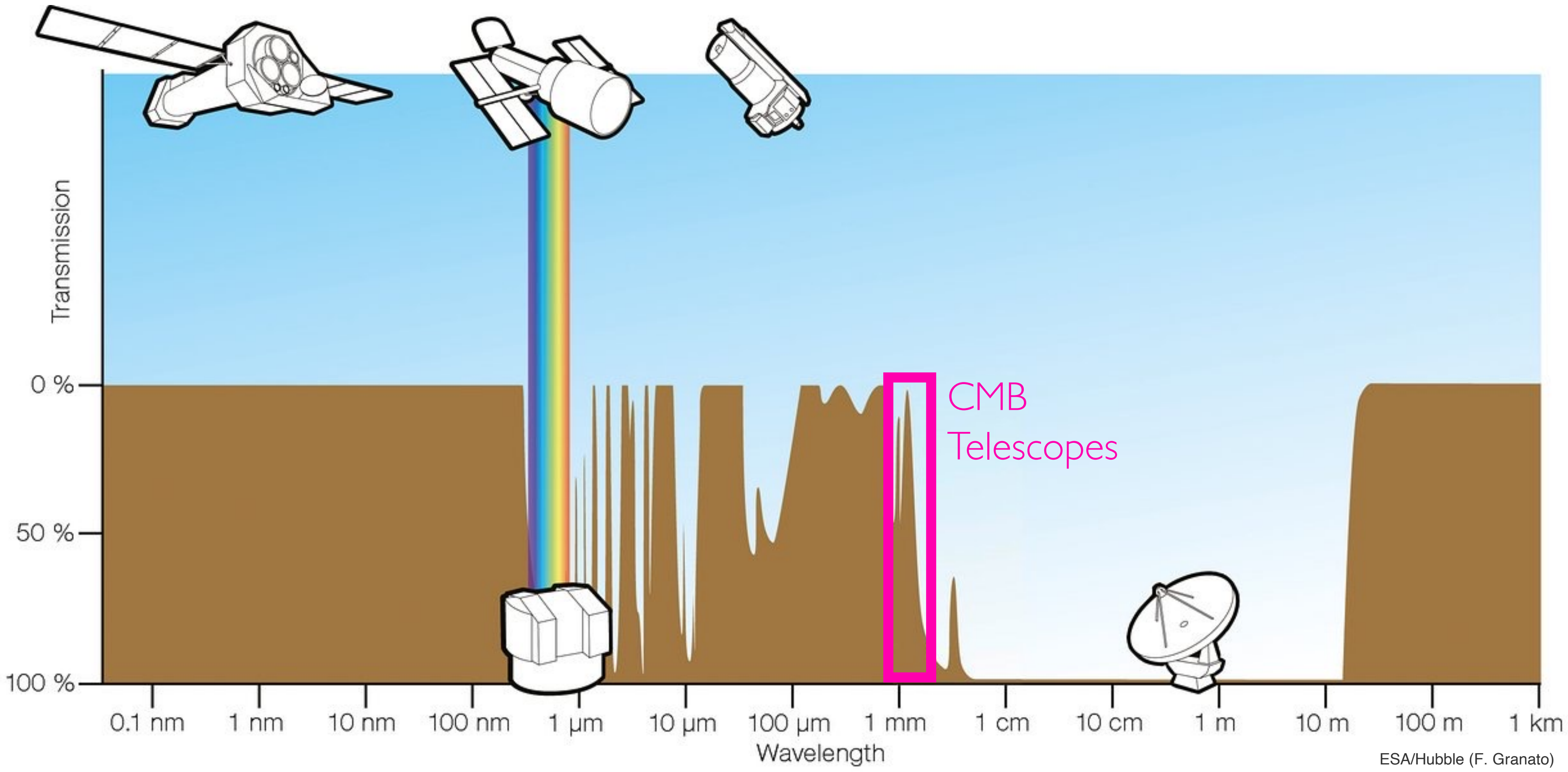
Matter Distribution

CMB-S4



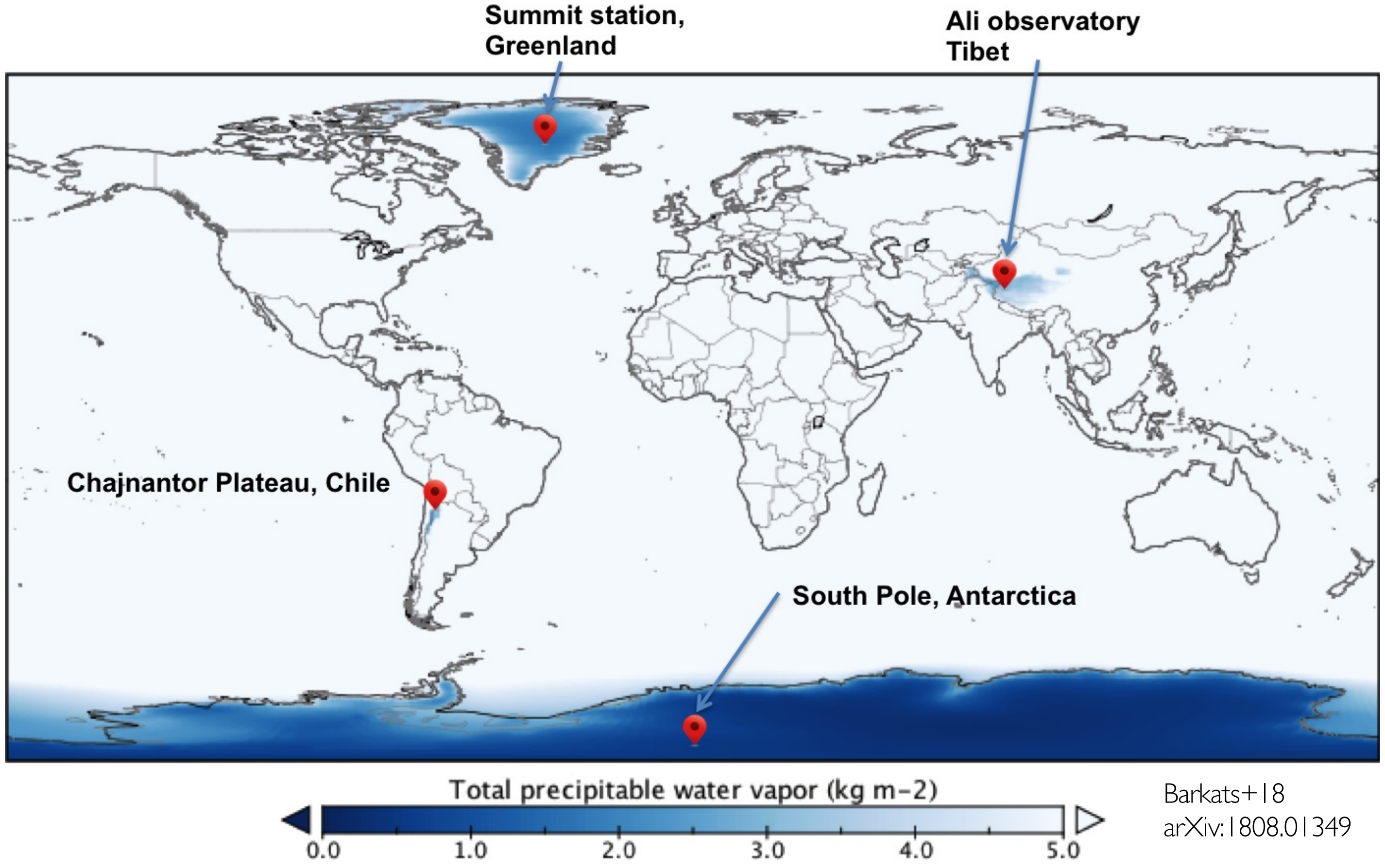
Polarization B-modes

The atmosphere limits our ability to see out into space.

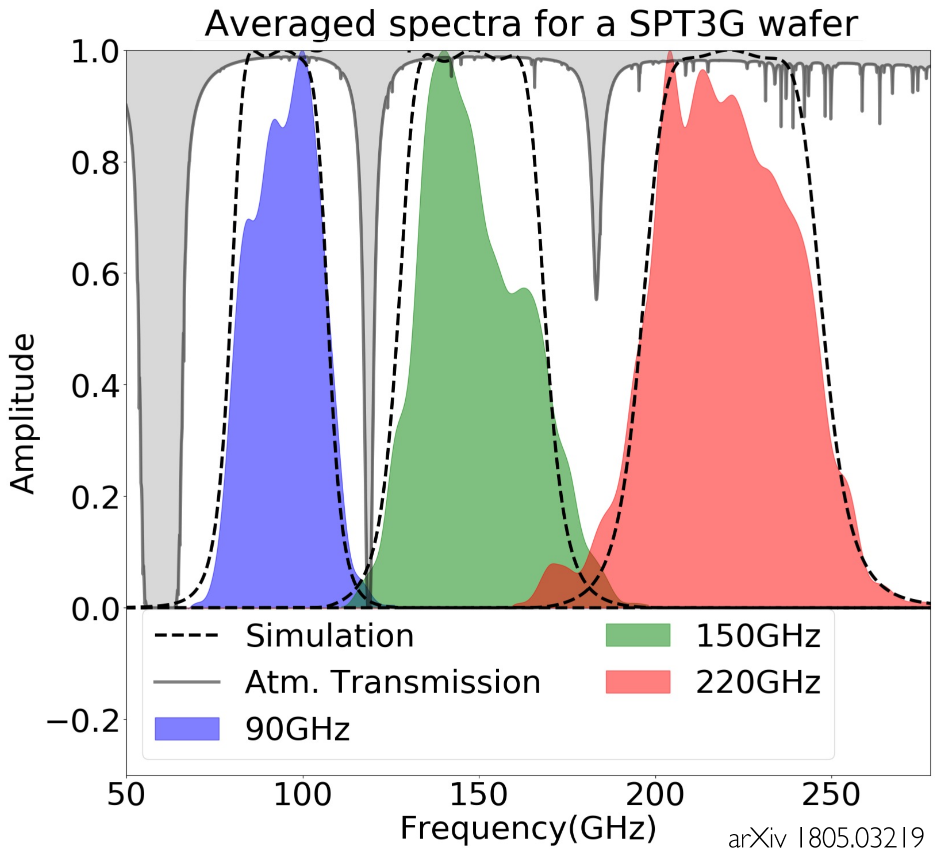


- Emission lines in the atmosphere attenuate astronomical signals and act as a thermal foreground.
- To observe from the ground, we have to use discrete spectral windows.

We can try to avoid atmospheric emission by carefully choosing location and observing bands.



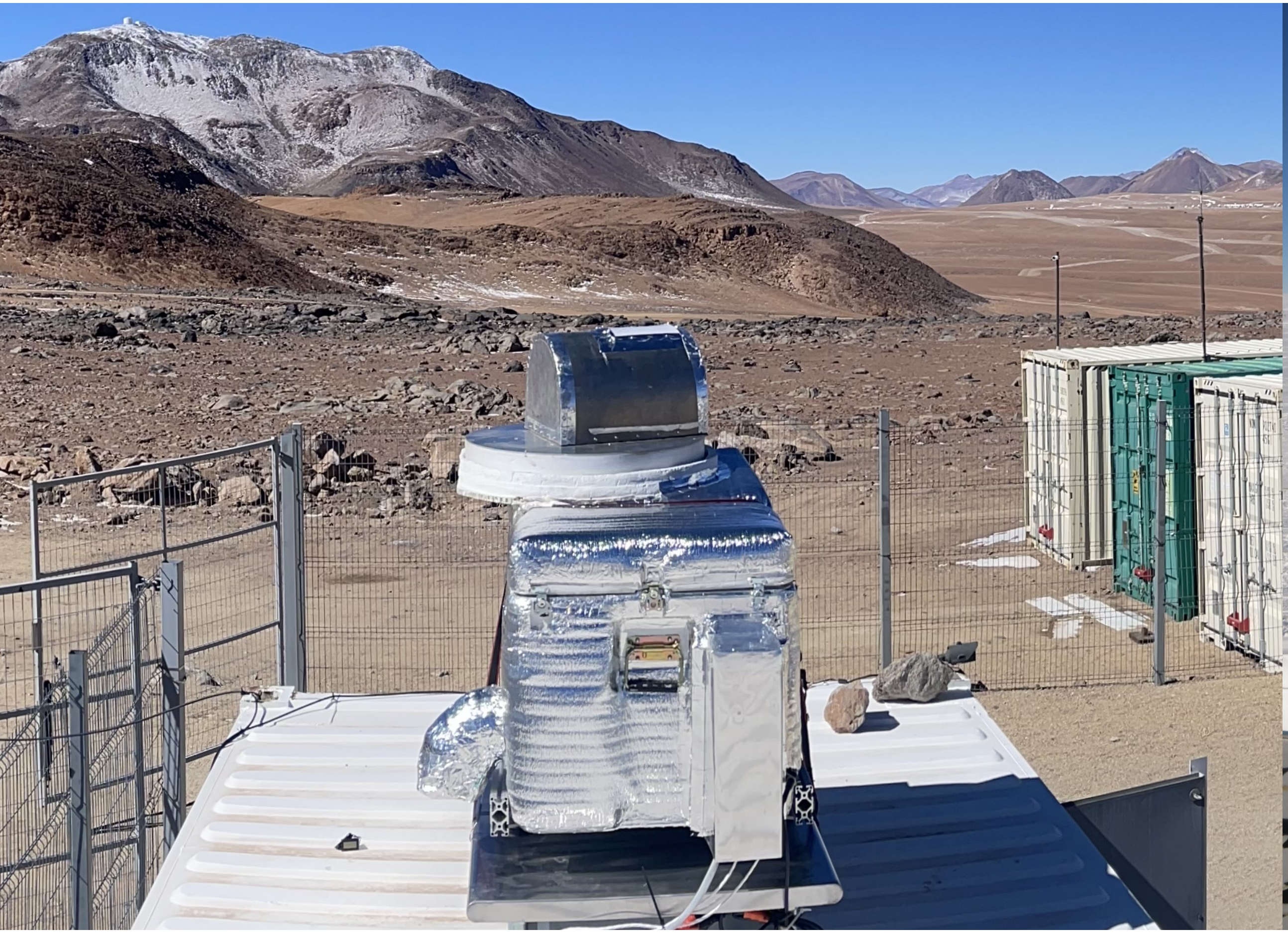
Barkats+18
arXiv:1808.01349

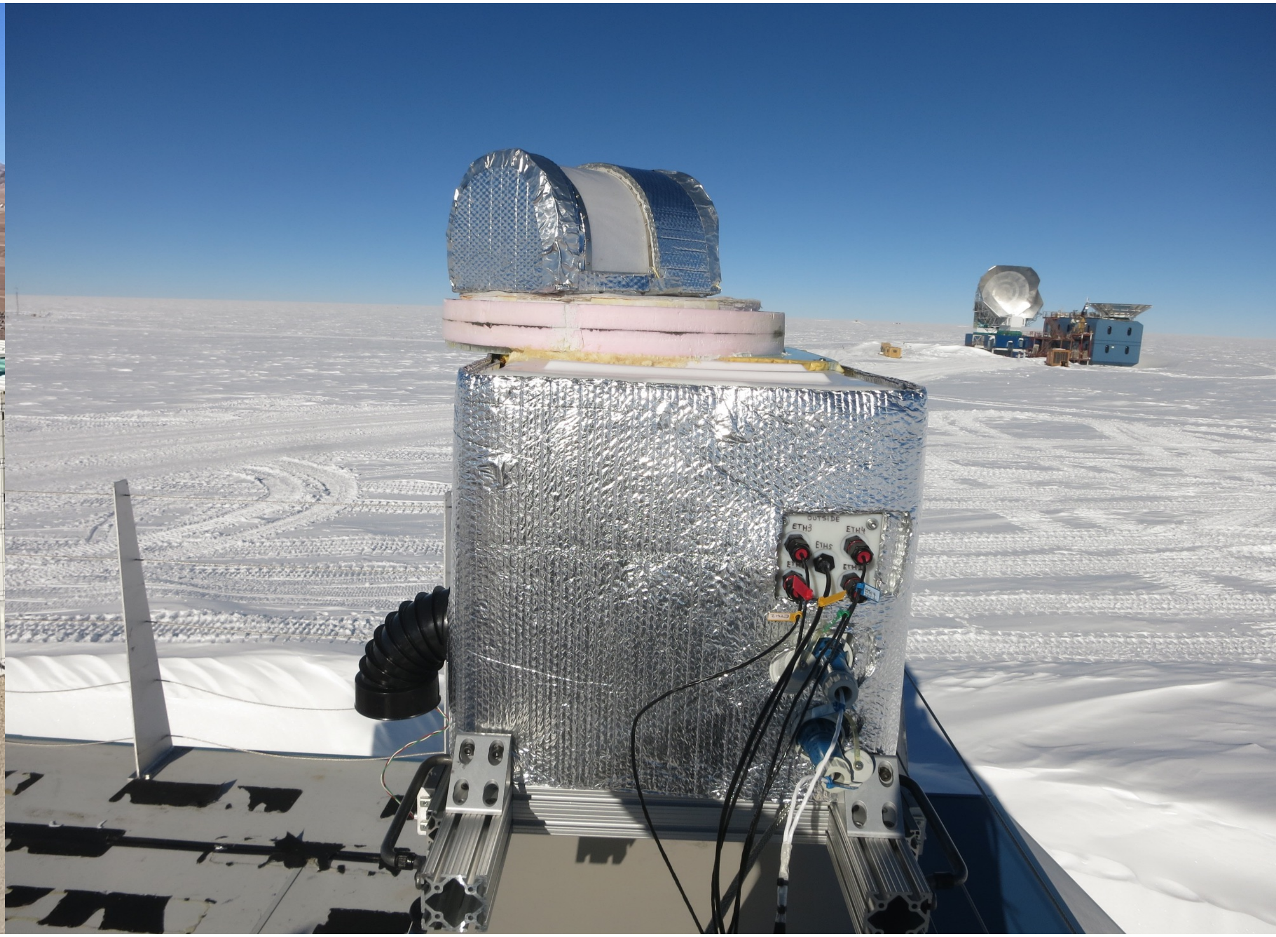


arXiv 1805.03219

PWV: 1 kg m^{-2} = 1 mm

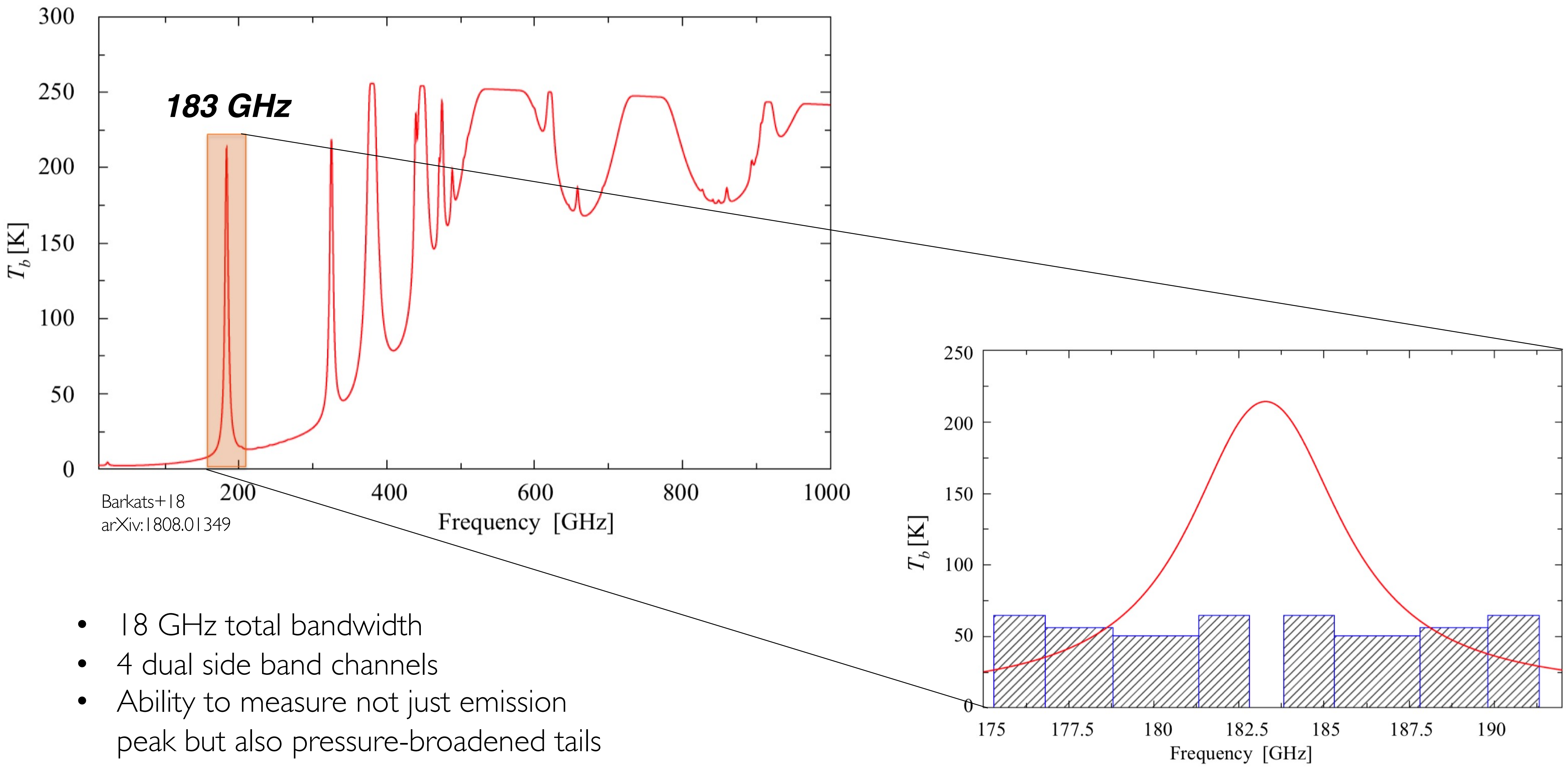
We measure the atmospheric water vapor at Cerro Toco, Chile and at South Pole using a pair of 183 GHz water vapor radiometers (WVRs).





Others contributing to these instruments include Denis Barkats, Darcy Barron, Ian Birdwell, Sofia Fatigoni, John Kovac, Matthew Petroff, Abigail Vieregg, with significant help maintaining them from other members of the BICEP/Keck and CLASS collaborations.

The WVRs target the 183 GHz water line between two key CMB bands.



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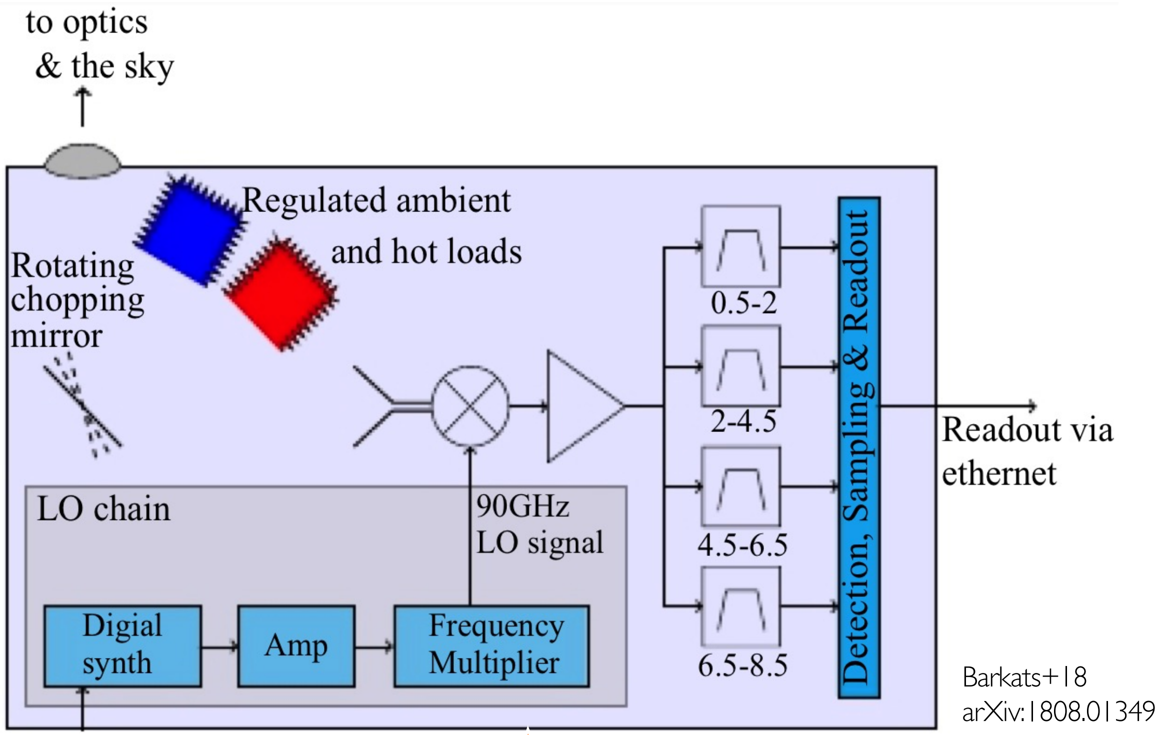
- 18 GHz total bandwidth
- 4 dual side band channels
- Ability to measure not just emission peak but also pressure-broadened tails

We use Dicke switched warm radiometers developed for ALMA by Omnisys.



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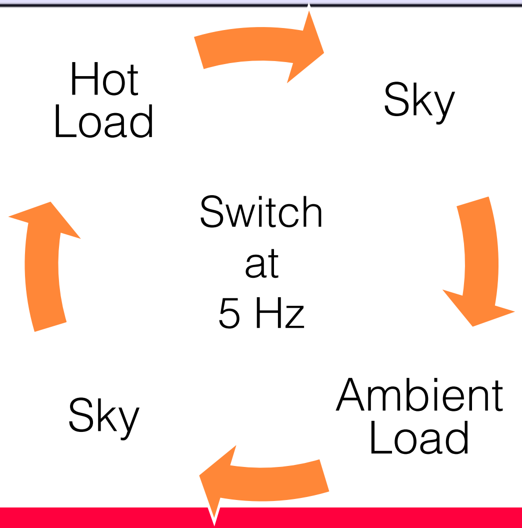

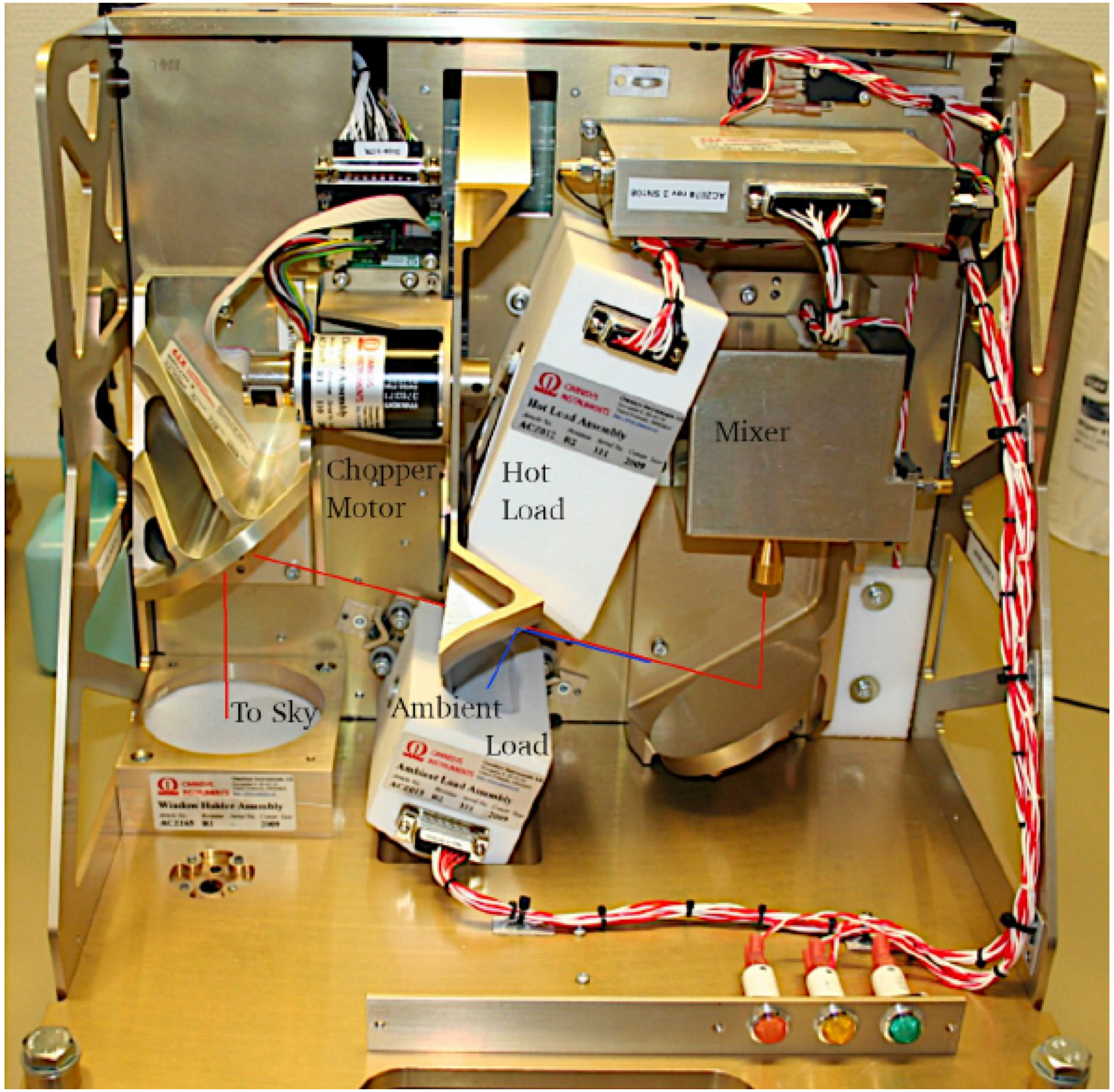

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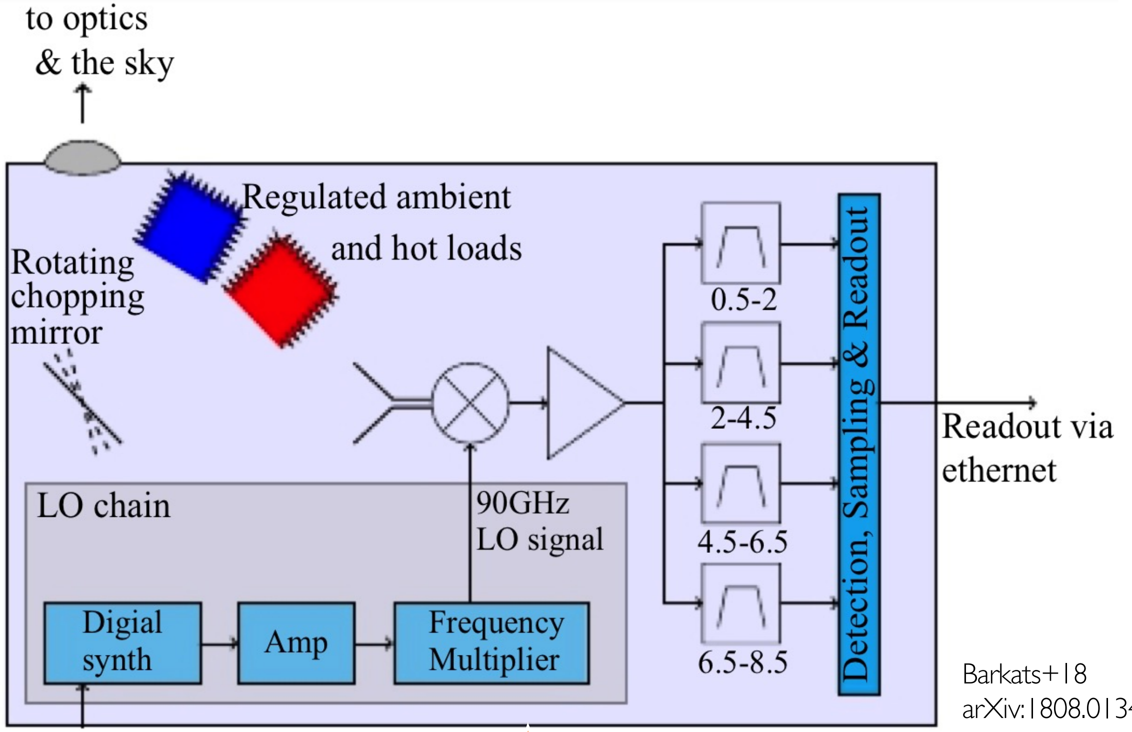

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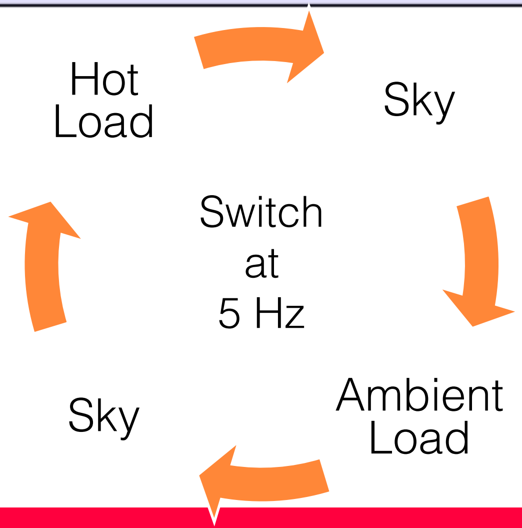
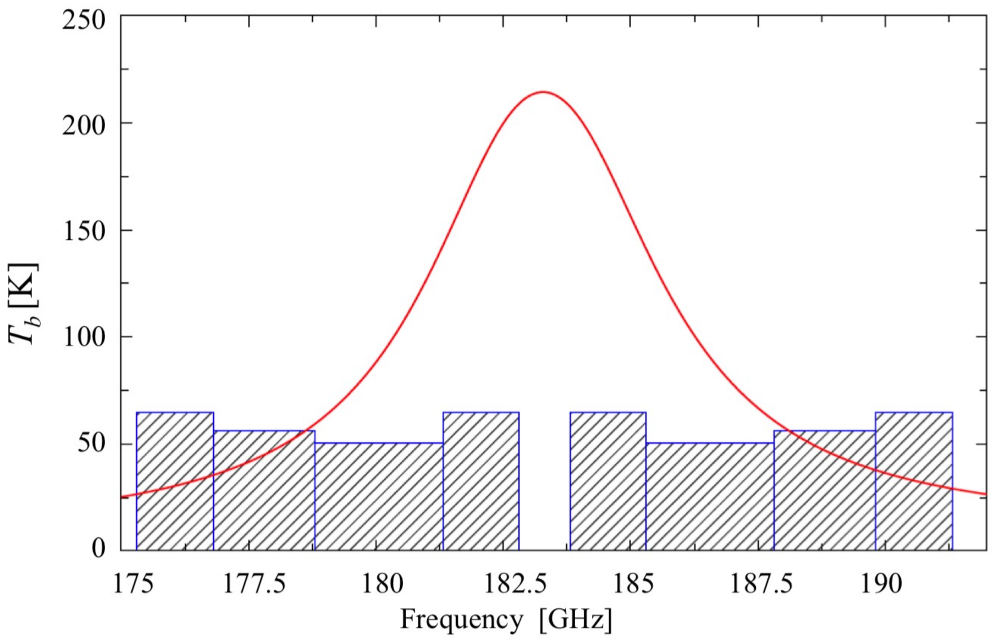
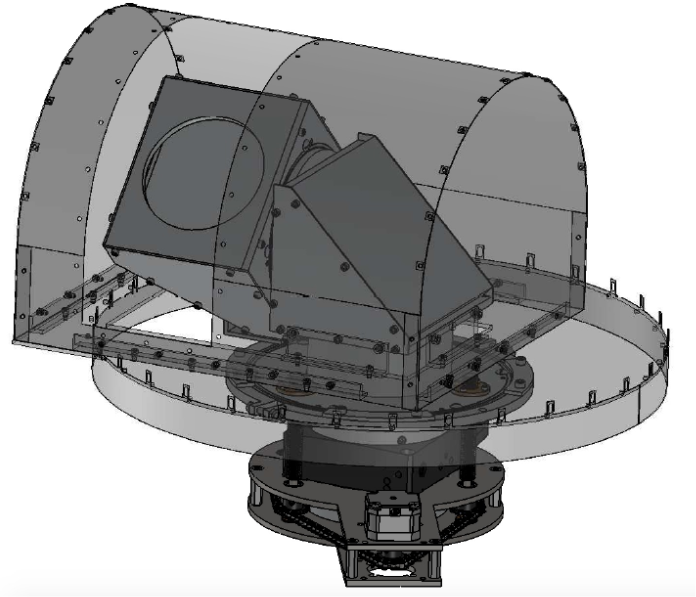


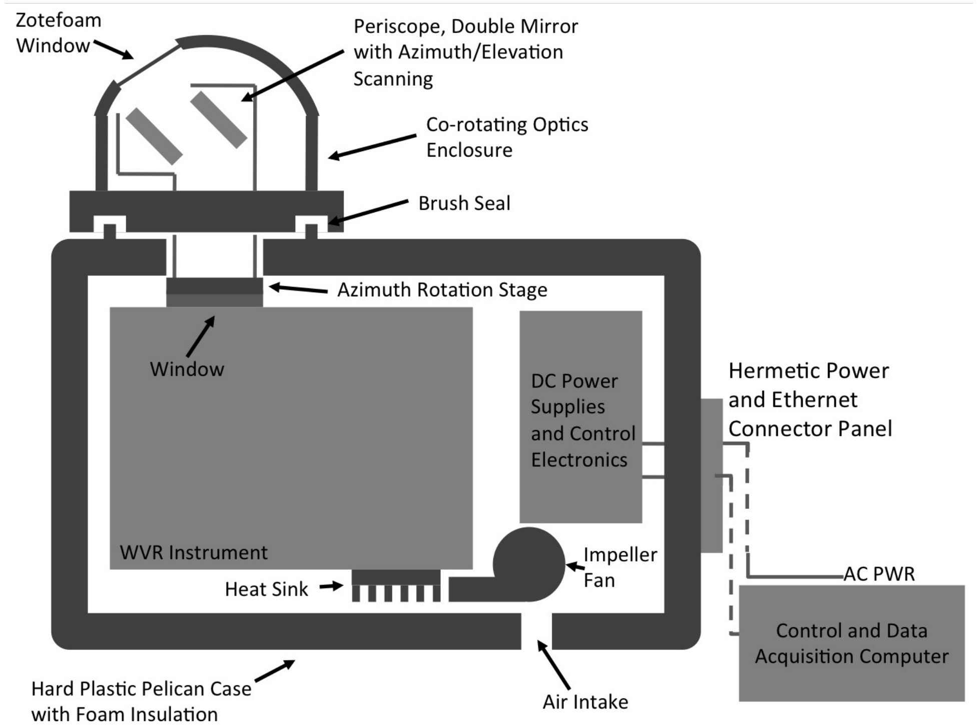
$$T_{src} = \frac{V_{src}}{\mathrm{mean}(G)} - \mathrm{mean}(T_{rx})$$

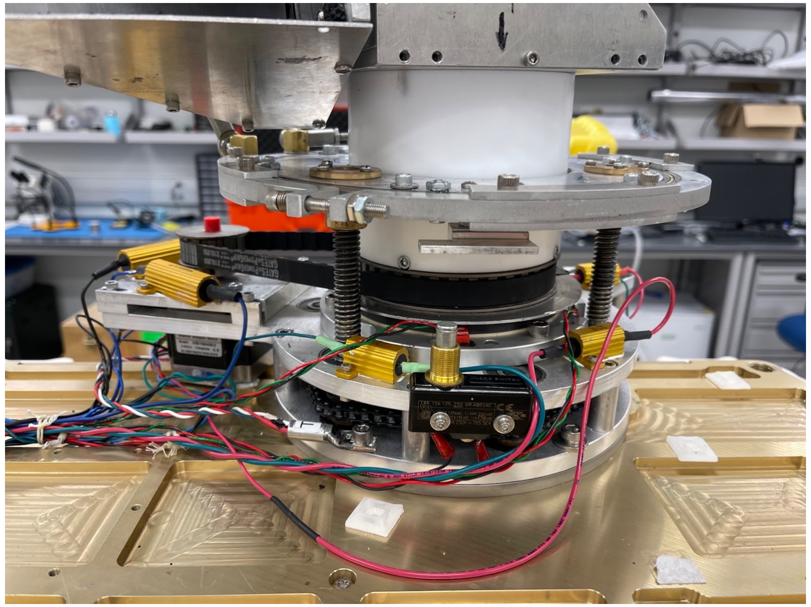
$$T_{rx} = \frac{V_c T_h - V_h T_c}{V_h - V_c} \qquad G = \frac{V_h - V_c}{T_h - T_c}$$



We also have custom optics and environmental controls.



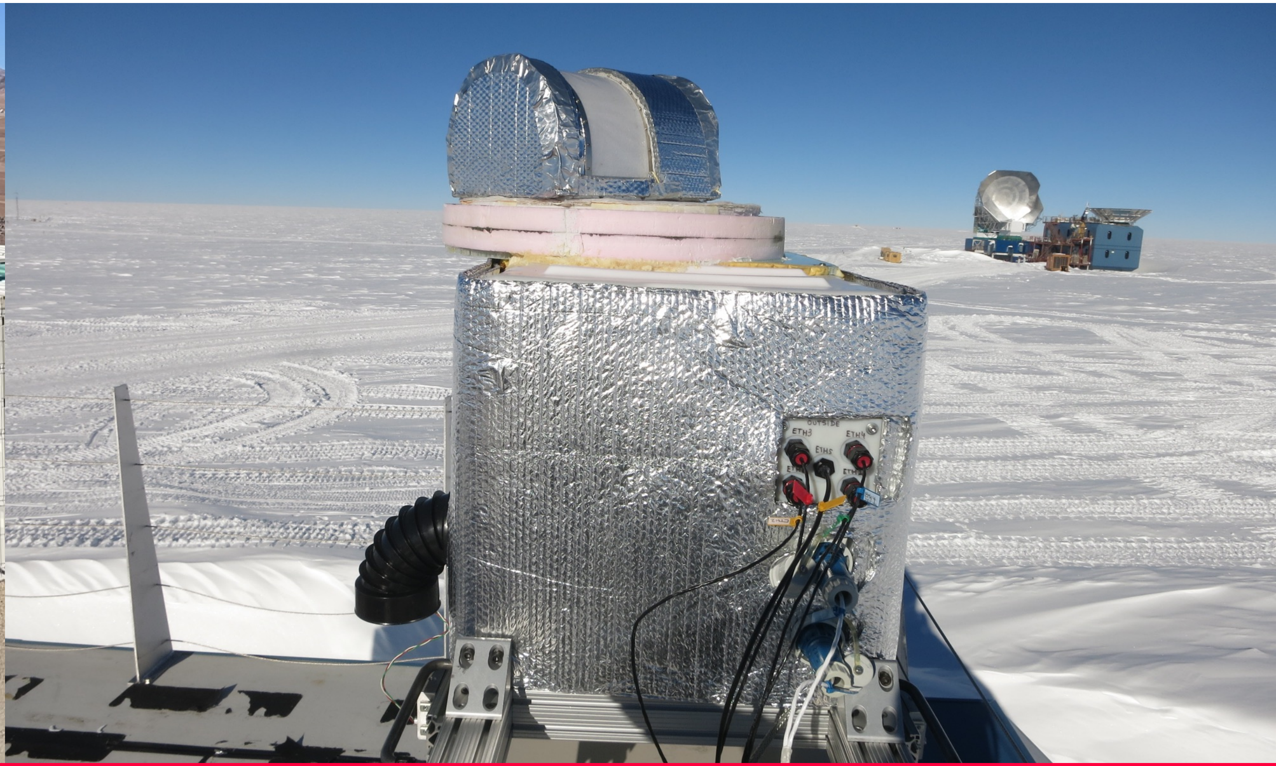




- Insulated pelican case enclosure with heaters and coolers
- PID temperature control via Arduino
- Internal temperature regulated to 18-22° C
- Beam FWHM ~3°
- Azimuthal rotation of 2 RPM

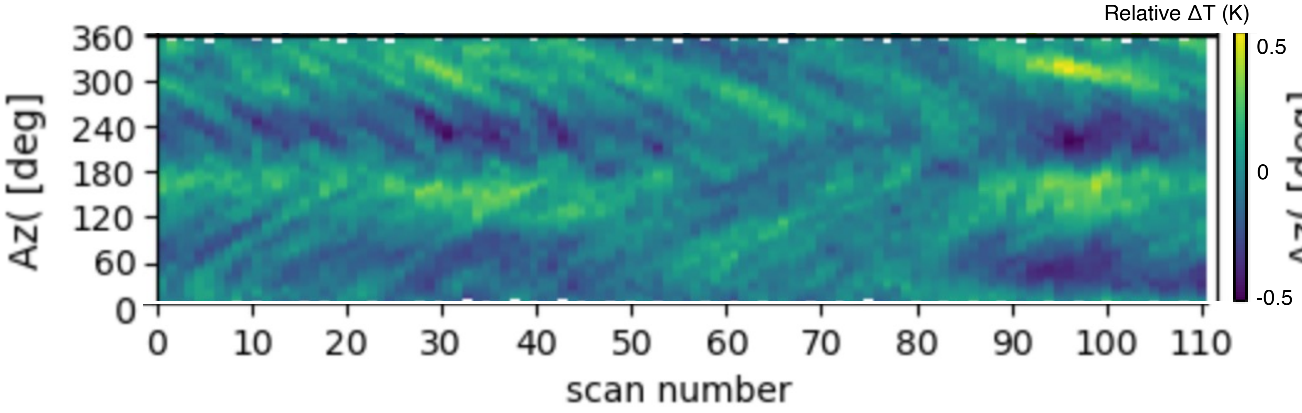
Both WVRs are currently observing.

- Continuous 360° azimuthal scans at 55° elevation
- Elevation sky dip from 15° to 90° every hour to get zenith temperature and opacity
- Observing strategy matches the cadence of BICEP receivers but is easily changeable
- **Sensitivity of 1μm** at or below 1 mm of PWV: equivalent to a **~5mK** temperature fluctuation at 150 GHz

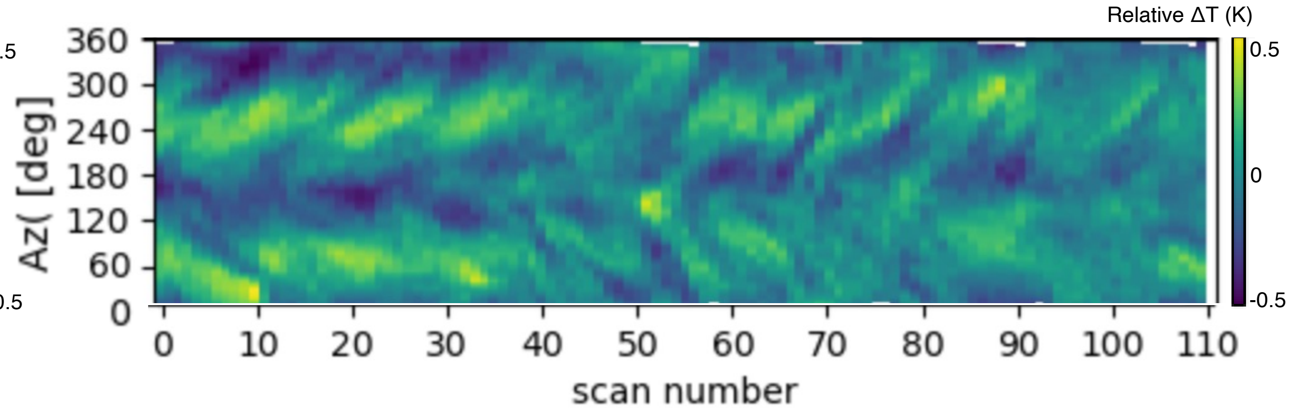


We can see clear patterns in the data due to weather.

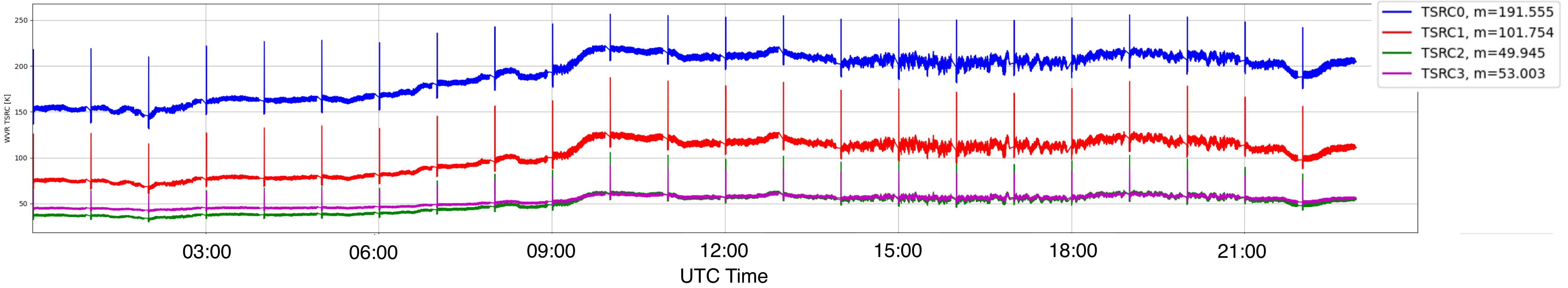
Winds from the west



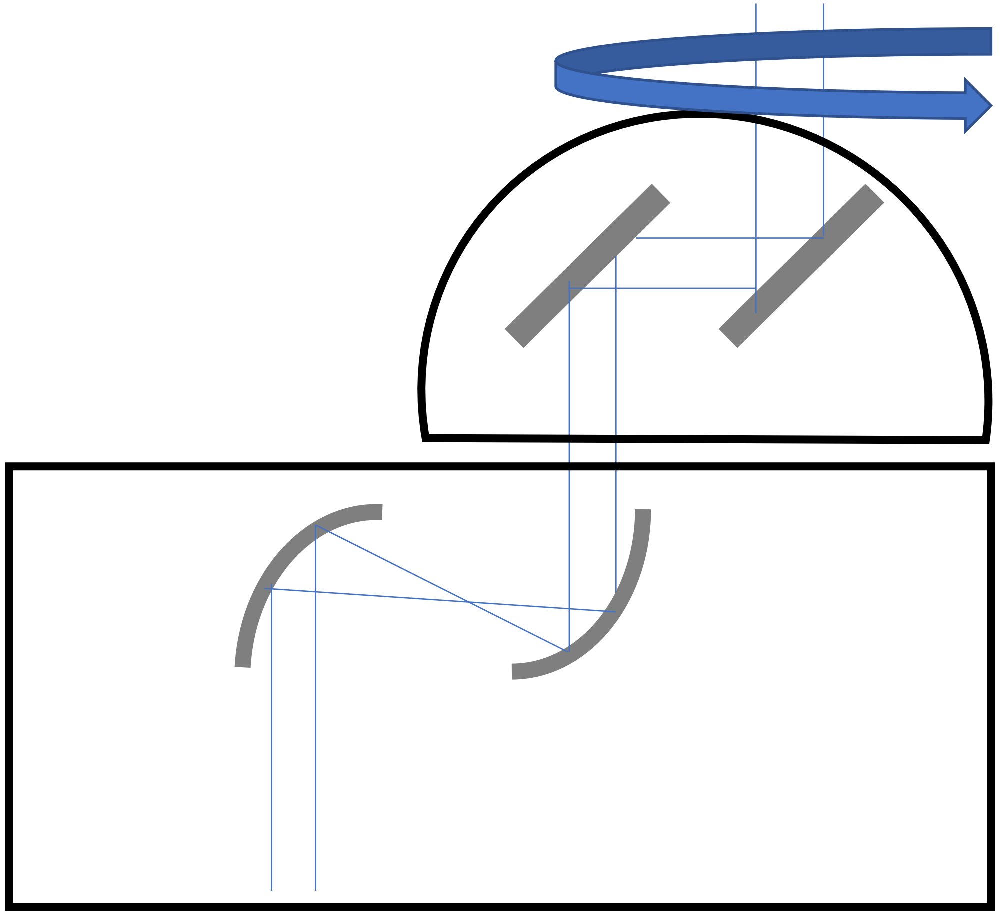
Winds from the east



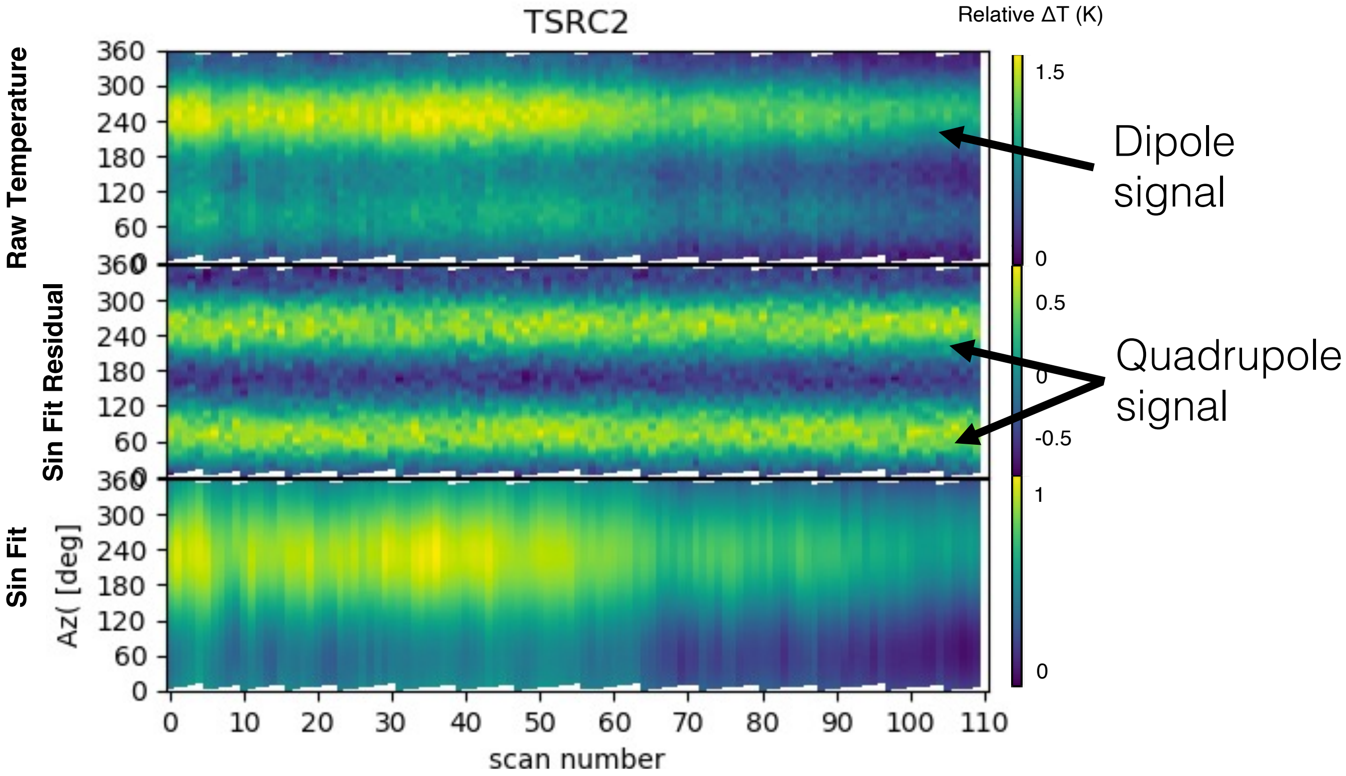
- Variations in spatial and temporal scales for vapor cells moving in and out of the field of view
- In Chile, sky temperature over 24 hrs. tracks local day/night cycle



Data require careful calibration to account for tilt and mirror rotation.



- Tilt with respect to ground causes dipole
- Rotation of flat 45° mirrors relative to curved mirrors causes quadrupole as slight mirror-induced polarization vector rotates during 360° scan

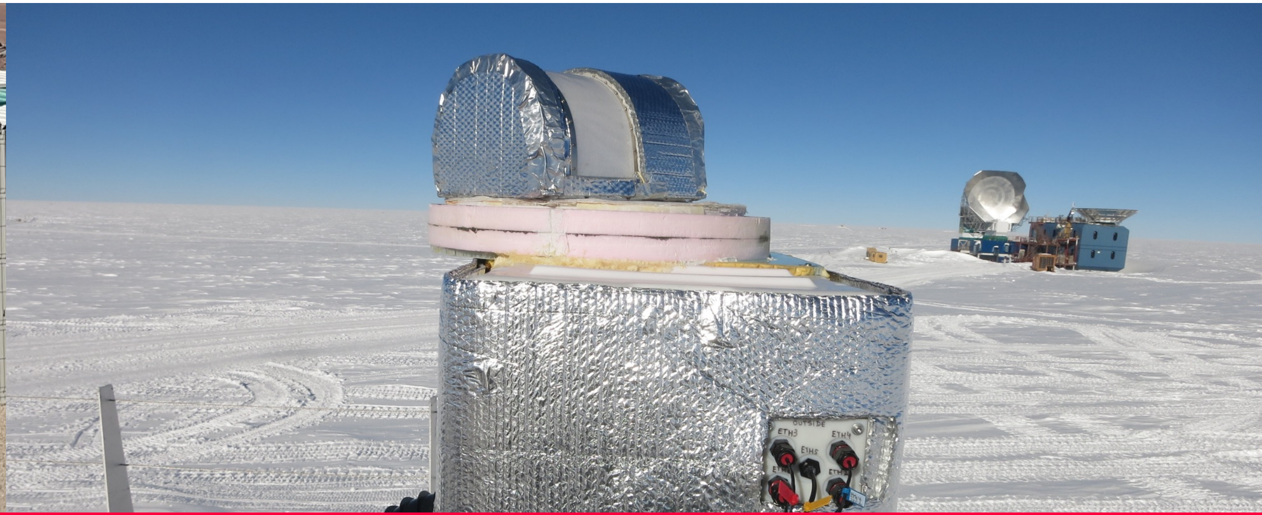


- We correct for instrumental effects by fitting 1Θ and 2Θ sinusoids.

Analysis is ongoing.

In-progress or planned:

- Assess data quality and instrument performance
- PWV calculations and comparisons with other independent measurements (e.g. MERRA-2, other radiometers, GPS)
- Characterize and quantify temporal and spatial scales of water vapor fluctuations
- Leverage identical instruments to directly compare observing conditions in Chile and at South Pole



Thank you!

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